RESULTS OF AN AIRBORNE ALBEDO PROGRAM IN ANTARCTICA, 1963

ANGELO F. SPANO

Atmospheric Analysis Laboratory, Environmental Science Services Administration, Washington, D.C.

ABSTRACT

A series of measurements of the albedo of various representative types of underlying surfaces was made from a specially instrumented aircraft during October and November 1963. In this operation, Phase II of an Antarctic airborne albedo measurement program, special flights were also made to determine corrections to the observed values for aircraft altitude and for aircraft orientation with respect to the sun.

A systematic variation in albedo values with differing aircraft orientation with respect to the sun was found, apparently because of a slight leveling error, and corrections computed for this factor were applied to the data. It was also discovered that albedo values decrease 1.2 percent for each 1000-ft. increase in altitude from the surface to 6000 ft., and remain relatively constant thereafter.

Albedo values of 83 percent were obtained for the polar plateau and 74 percent for the Ross Sea area for winter ice with no clouds below the aircraft. The albedo of stratocumulus clouds over these surfaces was 79 percent, and of altocumulus clouds 77 percent.

Albedo values as measured from the aircraft in the vicinity of the South Pole were in good agreement with surface measurements at this site.

1. INTRODUCTION

The albedo of various representative underlying surfaces in the Antarctic region is important in determining the radiation and heat budgets of that area. To permit an accurate evaluation of albedo, an airborne albedo measurement program was carried out during two austral summers by personnel of the Polar Meteorology Branch of the U.S. Weather Bureau's Atmospheric Analysis Laboratory. This paper constitutes a report on Phase II of the program, covering observations made during October and November 1963. Phase I observations (October and November 1962) have been reported on by Predoehl and Spano [6].

The objectives of Phase II were (1) to obtain additional data over the Ross Sea area to supplement similar data obtained during the previous summer in Phase I of the program; (2) to determine and correct for variations in measured albedos with different aircraft orientations with respect to the sun; (3) to determine how the measured albedo varied with respect to aircraft altitude; (4) to compare the albedo as measured from the air over the polar plateau and in the vicinity of the geographic pole with that measured at the surface at the South Pole Station; (5) to gather breaking-waves data for a wave research program, which is not further reported on here.

The aircraft used in this program was a specially modified and instrumented U.S. Navy C-54Q, and the base of operations was McMurdo Station, Antarctica (77°53′ S., 166°44′ E.). Radiation sensors employed were Eppley wide-band pyranometers, and data were recorded on a *Non-Linear* Systems recording digital voltmeter. More

TABLE 1.—*Times, tracks, and altitudes of flights on which albedo measurements were taken.*

Date	Flight No.	Run No.	Start Latitude °	′S	Start Longitude °	′	End Latitude °	′S	End Longitude °	′	Aircraft altitude above surface (ft.)
Oct. 1963											
24	1	1	67	36	164	45E	67	16	164	45E	8,000
24	1	2	67	14	164	30E	67	36	164	50E	8,000
24	1	3	67	36	164	32E	67	16	164	40E	7,500
24	1	4	69	30	170	30E	69	45	170	35E	7,100
24	1	5	69	30	170	45E	71	00	171	22E	6,900
28	2	1	76	25	167	30E	75	27	169	23E	5,000
28	2	2	74	00	170	20E	73	20	170	32E	5,000
28	2	3	73	13	173	00E	73	36	174	15E	5,000
30	3	1	77	56	169	50E	77	45	172	20E	5,500
30	3	2	77	56	169	50E	77	40	173	00E	5,500
30	3	3	77	45	171	30E	78	21	173	00E	5,500
30	3	4	78	21	173	00E	77	28	170	33E	5,400
31	4	1	78	30	164	30W	Bay of Whales area				5,500
31	4	2	78	30	164	30W	Bay of Whales area				5,500
31	4	3	78	20	173	25E	78	20	172	25E	10,000
31	4	4	78	04	171	10E	78	03	170	05E	7,950
31	4	5	77	48	170	00E	77	48	168	45E	6,050
31	4	6	77	39	167	23E	77	37	166	20E	4,000
31	4	7	78	04	167	30E	78	01	166	20E	3,000
31	4	8	77	50	168	05E	77	58	169	15E	2,000
Nov. 1963											
1	5	1	77	30	170	15E	77	42	170	50E	10,000
1	5	2	77	30	170	15E	77	42	170	50E	8,000
1	5	3	77	30	170	15E	77	42	170	50E	6,000
1	5	4	77	30	170	15E	77	40	170	30E	4,000
1	5	5	77	30	170	15E	77	41	170	39E	3,000
1	5	6	77	30	170	15E	77	42	170	50E	2,000
1	5	7	77	30	170	15E	77	42	170	48E	1,000
1	5	8	77	30	170	15E	77	43	170	47E	500
18	6	1	73	35	170	55E	73	38	167	50E	5,000
18	6	2	74	04	173	10E	73	44	167	38E	5,000
18	6	3	73	38	167	45E	72	38	170	28E	5,000
18	6	4	72	48	170	28E	72	30	171	15E	6,000
18	6	5	72	25	171	30E	72	50	170	10E	8,500
20	7	1	86	30	165	00E	87	20	165	10E	2,500
20	7	2	89	55	75	00W	89	55	105	00E	2,500
20	7	3	89	55	105	00E	89	55	75	00W	1,600
20	7	4	89	55	165	00W	89	55	45	00E	2,500
20	7	5	89	55	45	00E	89	55	165	00W	2,500
20	7	6	78	34	169	40E	78	30	169	00E	10,700
21	8	1	52	26	169	10E	52	46	169	00E	3,350
21	8	2	52	46	169	07E	52	32	169	15E	3,100
21	8	3	52	32	169	15E	52	24	169	10E	3,100
21	8	4	52	28	169	15E	52	28	169	07E	3,200

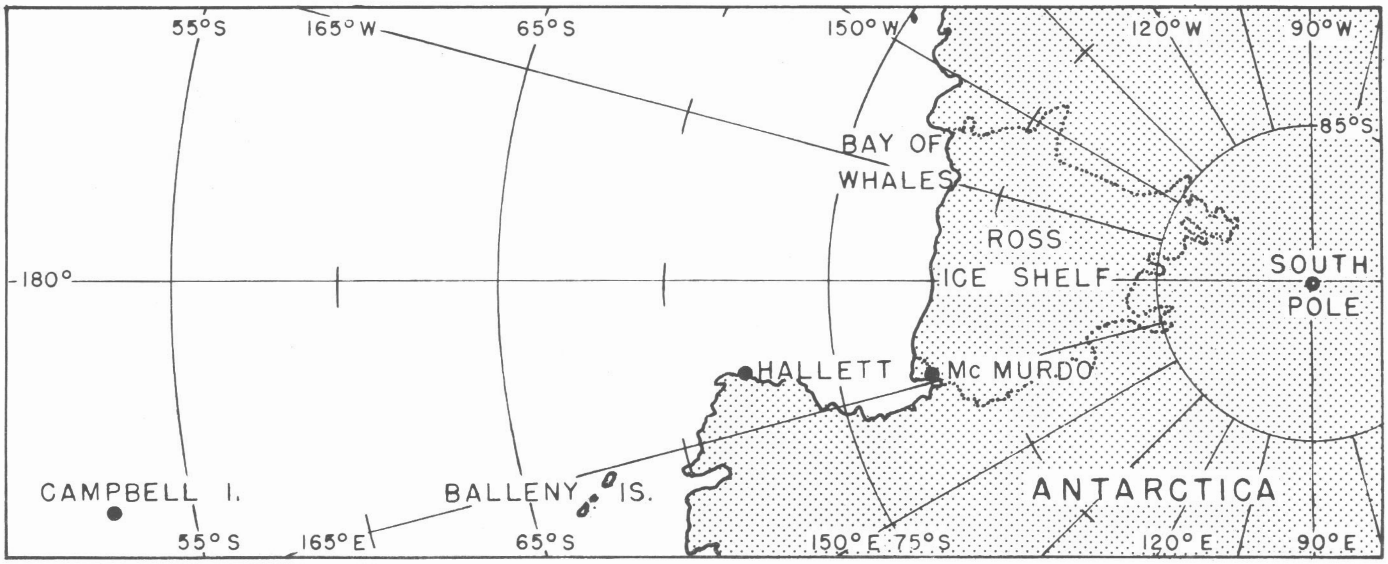

FIGURE 1.—General area of albedo flights made during October-November 1963.

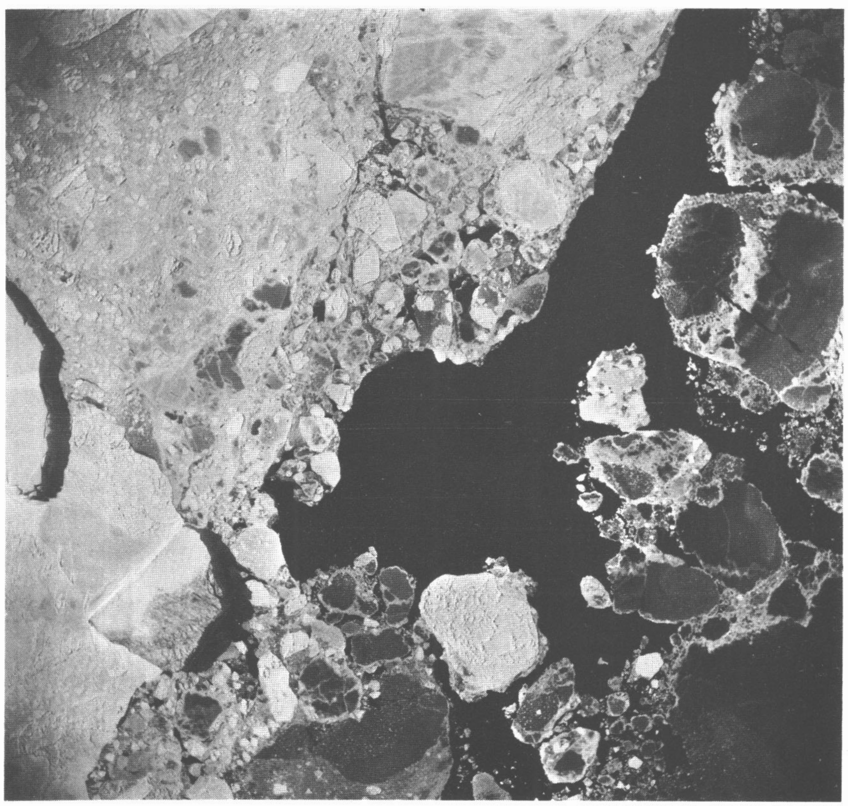

FIGURE 2.—Surface composed of old winter ice, new winter ice, young ice, open water, and icebergs.

detailed descriptions of instruments, equipment, and operations are included in the report on Phase I of the program by Predoehl and Spano [6], hence are not included here.

Successful flights were made on a total of eight days during October and November 1963 (see table 1). Figure 1 is a map of the general area where the flights were made. The problem of the extreme cold adversely affecting the recording equipment was alleviated by preheating the printing mechanism with a portable flood lamp. Photographs of the underlying surface were taken from the aircraft simultaneously with the radiation observations and at equally-spaced time intervals to provide about 60 percent overlap between successive photographs. Figure 2 reproduces one such photograph, showing a surface composed of old winter ice, new winter ice, young ice, open water, and icebergs. To coordinate the photographs with the radiation-recording tape the photograph number was marked on the recording tape at regular intervals.

2. DATA ANALYSIS

To try to determine, and correct for, variations in recorded radiation values resulting from differing orientation of the aircraft relative to the sun, special flights were made to evaluate such variations. On two flights, runs were made back and forth along a line toward the sun's position, and along a line normal to the direction of the sun. Data from these flights are shown in figure 3.

Examination of the data indicates that the upfacing pyranometer registered higher values when the aircraft was flying toward the sun and with the sun on the right side of the line of flight, as compared with the values recorded while flying in the two opposite directions. If all other factors were equal, the values should be independent of aircraft orientation with respect to the sun. In particular, the solar elevation angle and sky conditions were the same for the runs in all four directions on the flight of November 20, 1963, and the results from this flight were used to determine the magnitude of the variation. The variations may be explained by the sensing surface of the instrument actually having a slight tilt toward the nose and right side of the aircraft when the bubble level on the instrument was properly centered.

As this seemed the most likely explanation, the angular deviation from true horizontal necessary to produce the variations observed in the flight on November 20 was determined for each of the four directions relative to the sun. These angular deviations were then applied to all of the albedo data to correct for sun azimuth with respect to the aircraft (and sensor). Figure 4 shows curves of the multiplying factor by which to correct the observed data for this error at sun elevations fron 5° to 55°.

Table 2 shows average values of radiation and albedo data for the flight made over the South Pole on November 20, 1963. As can be seen in the table, the difference between the albedo values with the correction derived above and those with an adjustment of −1.2 percent for each

TABLE 2.—*Comparison of radiation and albedo measurements at the surface and from aircraft at the South Pole, arranged according to aircraft orientation with respect to the sun.*

		Radiation (ly./min.)		Albedo (percent)		
		In-coming	Re-flected	Meas-ured	Corrected for sun azimuth with respect to the aircraft	Adjusted for altitude: −1.2 percent/1,000 ft.
Sun ahead	Surface	0.5574	0.4603	83		
	2,600 ft	.528	.404	76	79.4	79.5
Sun behind	Surface	.5604	.4660	83		
	1,600 ft	.485	.411	85	81.1	81.3
Sun right	Surface	.5605	.4647	83		
	2,500 ft	.534	.409	76	79.9	79.9
Sun left	Surface	.5629	.4667	83		
	2,500 ft	.480	.407	85	80.5	79.9

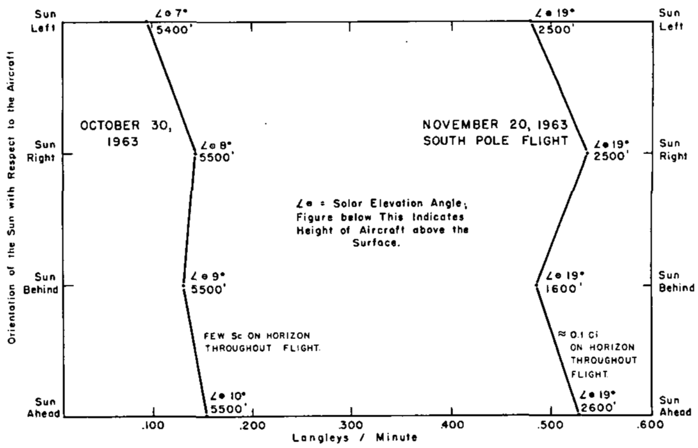

FIGURE 3.—Plots of incoming solar radiation data showing different values at various positions of the sun with respect to the aircraft.

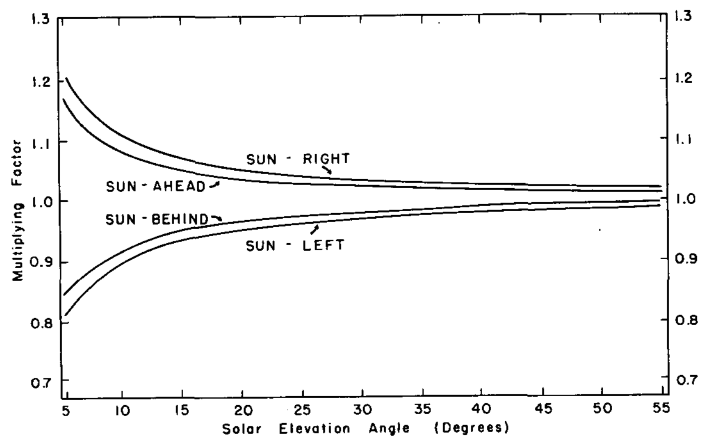

FIGURE 4.—Graph of multiplying factors used in correcting albedo values for sun azimuth

1,000-ft. increase in altitude from the surface (to be discussed later) is within a reasonable limit of error. The surface instrument (#3070) and pyranometer #4361 (the aircraft instrument) were subsequently compared with each other during November 1964 at the South Pole. Figure 5 presents the results of these comparisons. Both instruments, while being compared on the surface, had a frost accumulation problem. However, this was not the case when #4361 was utilized during the flights. It was also noted that the curve of #3070 had a diurnal sinusoidal character. Because of these two problems, the segments of the curves presented in figure 5 were selected so that average output conditions of both instruments can be easily observed. Examination of the data indicates that the incoming radiation values for #4361 are substantially lower than those of #3070. This difference is also evident in the data presented in table 2. The aircraft instruments and those used at the surface at the South Pole are of different types. It appears from the data in table 2 that one, or both, of these types does not measure the solar

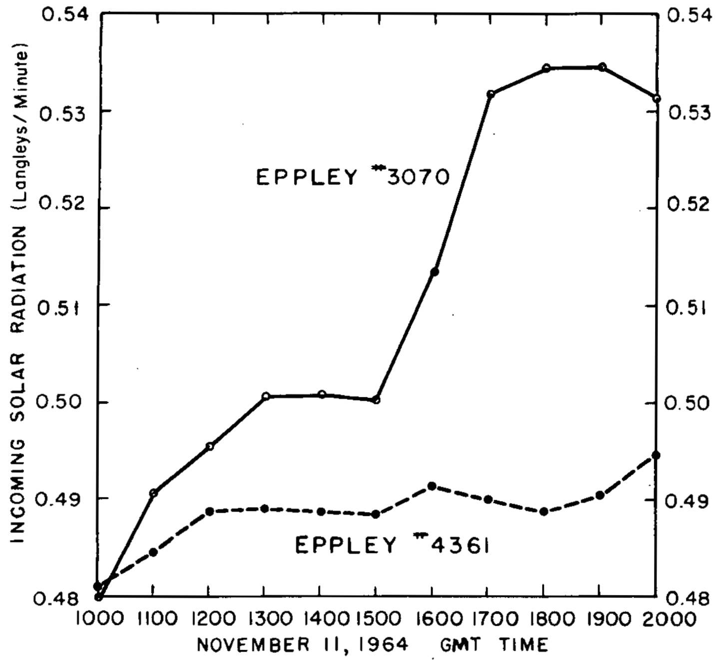

FIGURE 5.—Comparison of Pyranometer Nos. 4361 and 3070 at the South Pole Station.

radiation with absolute accuracy, but whatever error is present is consistent for a given type; thus, while the absolute values of either incoming or reflected radiation may be questionable, the albedos derived seem reliable, if instruments of the same type are used to measure both incoming and reflected radiation.

Further checks with pyranometer #4361 were conducted at the U.S. Weather Bureau's Test and Evaluation Laboratory, Sterling, Va., during September 1964, in order to provide a check on the apparent leveling error of this instrument. The pyranometer was placed at the four positions, with respect to the sun, and incoming radiation values were obtained from a portable potentiometer. Curves of these tests are presented in figures 6 a and b. These data indicate that pyranometer #4361 registers higher incoming radiation values, when installed in the aircraft, if it faces the sun, and with the sun at the right side, than when the sun is at the two opposite directions. This was consistently the case when cirrus did not obscure the sun's disc.

The correction determined above has been applied to all 1963 data analyzed for use in this paper. A similar error was evident in the 1962 data, but the correction factor cannot be established because no flights were specifically flown for this purpose.

Most representative of the multiple-level flights is that of November 1, 1963. Here the flight was made over the uniform surface of the Ross Ice Shelf. Each run was flown over approximately the same area (see table 1), and the observed mean values of radiation and albedo are presented in table 3. The average sky condition for the

TABLE 3.—*Measured albedo of the Ross Ice Shelf as a function of aircraft height, November 1, 1963*

Height (ft.)	Solar elevation angle (deg.)	Measured albedo (percent)	Albedo corrected for sun azimuth with respect to the aircraft* (percent)
10,000	23	75	78.2
8,000	22	76	79.4
6,000	21	74	77.6
4,000	20	76	79.8
3,000	19	80	84.2
2,000	18	78	82.4
1,000	17	82	86.8
500	15	81	86.5

*Sun was to the right of the aircraft at all levels.

entire flight was nine-tenths high (approximately half thick-half thin) cirrus. Figure 7 shows that the albedo is inversely related to an increase in altitude of the aircraft. Without taking the variation of the solar elevation angle (from 23° to 15°) into account, it was found that the decrease of the albedo from the surface to 6,000 ft. is approximately 1.4 percent for each 1,000-ft. increase in altitude. If the data are corrected by variations in solar elevation, using corrections determined by Liljequist [4] (see his figure 46, p. 89), the albedo values are 1.2 percent lower for each 1,000 ft. increase in elevation up to 6,000 ft. There is no decrease apparent with altitude increases above 6,000 ft.

A similar multiple-level flight was flown over the Ross Ice Shelf on October 31, 1963. However, the terrain underneath was not homogeneous (mountains, land, moraine deposits, as well as undisturbed shelf ice were encountered); therefore, the data could not be used in assessing the variation of the albedo with altitude.

Data from table 3 and from the flights of October 30 and 31, 1963 were used to determine the average albedo of the Ross Ice Shelf. This value is 80 percent for solar elevation angles between 7° and 23°, and with an average sky cover (cirrus) of four-tenths through nine-tenths. Belov's [1] albedo of 79 percent in one case for the Shackleton Ice Shelf is almost identical to the above-mentioned value, but in a second case his albedo of 51 percent is considerably lower. It appears that he attributes this lower value to the correspondingly lower solar elevation angle, explaining that on the polar plateau (shelf ice is not mentioned) the "reddening" of solar radiation with a decrease of solar altitude, and the shadows cast on horizontal areas of the snow surface by the tops of sastrugi are the cause for the lower values. In a laboratory type of experiment with a piece of river ice, conducted by Lyubomirova [5], similar results to those of Belov were obtained. Whether or not Lyubomirova's data can be compared with any Antarctic measurements is a moot point, because of the fact that the experiment was not conducted under Antarctic conditions. Liljequist [4] at Maudheim, on the other hand, found that the albedo is inversely related to an increase in solar elevation angle. In any case, no conclusions can be formed here about the

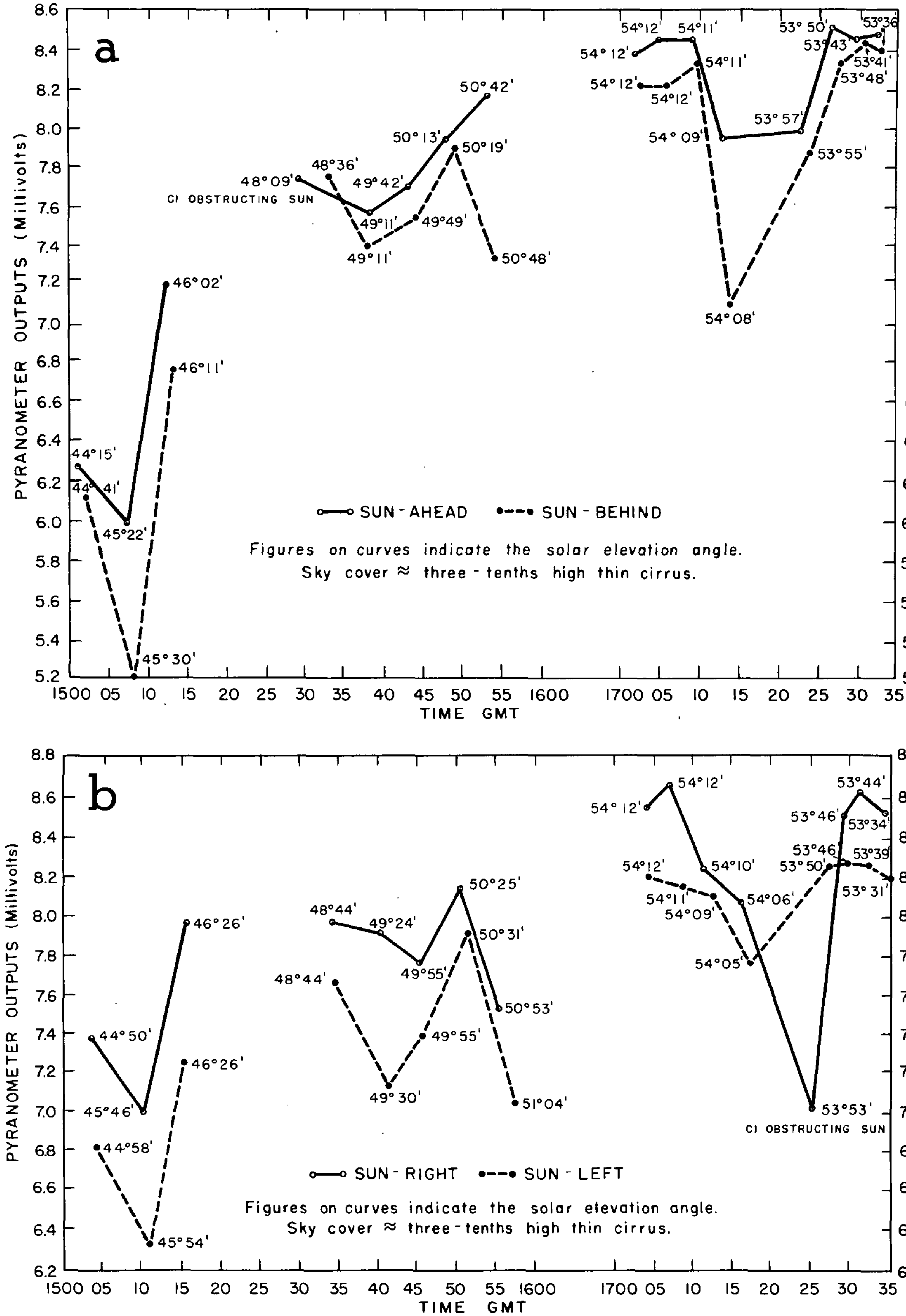

FIGURE 6.—Curves of tests with Pyranometer #4361 conducted at the U.S. Weather Bureau Test and Evaluation Laboratory, Sterling, Va. on September 17, 1964: (a) with sun ahead and behind (b) with sun left and right.

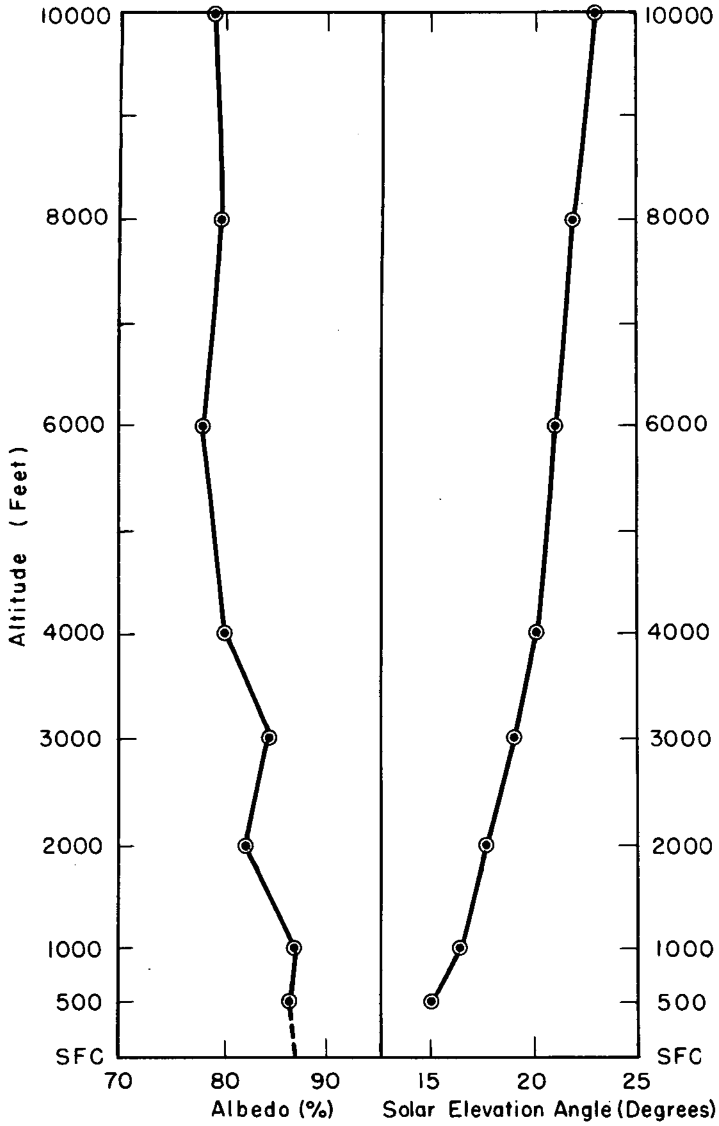

FIGURE 7.—Variation of albedo with altitude. Flight of November 1, 1963.

relationship between albedo and solar elevation angle because a much larger amount of data (such as was obtained on the surface by Liljequist) is needed for a study of this type.

Unfortunately it was not possible to obtain measurements of underlying surfaces which were exclusively either new winter ice, young ice, or open water. In the absence of these data (except for measurements taken over solid old winter ice, and the polar plateau) average albedos had to be derived from 44 observations of the flights of October 28, October 31, November 18, and November 20, 1963 which were made during periods when the sky was clear or nearly clear (≈ 0.1 to 0.2 coverage). Solar elevation angles varied from 11° to 32°. These data are presented in table 4 and are for coverage of an area in tenths of new and old winter ice combined (the remaining portion of the area is a combination of young ice and open water), and the polar plateau. The shelf ice albedo of 80 percent mentioned above is also presented in the table. Data were not available for less than four-tenths coverage of an area by winter ice.

TABLE 4.—*Mean albedos of various coverages of new and old winter ice in the Antarctic region.*

Tenths of combined new and old winter ice (snow covered)	Albedo (percent)
4	41
5	48
6	59
7	61
8	64
9	67
10	74
10/10 Shelf Ice	80
10/10 Polar Plateau	83

The mean albedos for ten-tenths coverage of an area by winter ice, and shelf ice are somewhat higher than the values found by Predoehl and Spano [6]. This can be partly explained by the fact that these two studies were not made during identical time periods or over the same area. It was found that the polar plateau with sastrugi has an albedo of 83 percent. The albedo of stratocumulus clouds is 79 percent, and altocumulus clouds yielded a value of 77 percent. In deriving the albedos of the polar plateau and the clouds, only one case for each underlying surface was available for analysis. Measurements (also only one case) were made under a layer of stratocumulus clouds (overcast) with an underlying surface of combined three-tenths old winter ice, three-tenths new winter ice, one-tenth young ice, and three-tenths open water. The albedo in this case was found to be 58 percent, compared to the mean albedo of 59 percent for six-tenths combined old and new winter ice. Five cases of measurements taken beneath altocumulus clouds are presented in table 5.

Considering that there have been very few airborne albedo programs conducted in the Antarctic, it is interesting to compare the values of different underlying surfaces discussed above with those of Belov's [1] airborne measurements. There is a close correspondence between the above-mentioned 83 percent albedo for the polar plateau and that of 80 percent measured by Belov for the same type of surface. This close agreement does not hold for cloud albedos; Belov's values are much lower: 62

TABLE 5.—*Measured albedos beneath altocumulus clouds over the Ross Sea.*

Tenths of combined new and old winter ice (snow covered)	Albedo—(percent)	Albedo—(percent) beneath altocumulus
8	64	53
9	67	58
9	67	60
8	64	53
9	67	61

percent for stratocumulus clouds and 69 percent for altocumulus clouds. However, his measurements were made over the open sea for stratocumulus clouds, and, presumably, also for the altocumulus clouds (although it is not specified in his paper). It can, therefore, be inferred that the albedo of clouds is much higher if the clouds are over an ice surface than if they are over open water, because of the higher reflectivity of the ice surface, provided the clouds are sufficiently thin so as to transmit a considerable portion of the light striking their lower surfaces, as appears to be the case here.

Another close agreement is the mean albedo value of 67 percent for nine-tenths winter ice, as compared to 70 percent estimated by Gabites [2] for an area coverage of nine-tenths pack ice (presumably old winter ice). For permanent ice and snow cover the 90 percent assumed albedo of Gabites is higher than the albedo reported in this paper for any type of snow and ice surface.

Observations were also made over Campbell Island on the return flight to New Zealand. The data gathered over this area are somewhat doubtful because of the severe turbulence and extensive cloudiness encountered by the aircraft, and so were eliminated from use in the albedo determinations.

3. CONCLUSIONS

In conclusion it can be mentioned that sources were searched for other possible comparison values, but all, insofar as albedo is concerned, proved to be irrelevant to the current study. Literature on airborne albedo measurements was available for areas other than Antarctica, but values presented therein varied markedly from albedos reported in this paper. Hanson's [3] results for the Arctic, in which it was expected to recognize comparable values to those of Antarctica because of the somewhat similar underlying surfaces, also indicated much lower albedos than those measured in the Antarctic during the current work. Hanson's lower values may be explained by the fact that he used ice with puddles for his measurements, whereas puddled ice is rarely found in Antarctica. Consequently, albedo values of the Arctic are generally lower than those of the Antarctic. The uniqueness of the Antarctic environment, and the impracticability of simulating conditions in the laboratory contribute to the difficulty of finding a correlation between measurements made in Antarctica and those made in other areas.

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